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PREPARATION OF MIRROR COATINGS
FOR THE VACUUM ULTRAVIOLET
IN A TWO-METER EVAPORATOR

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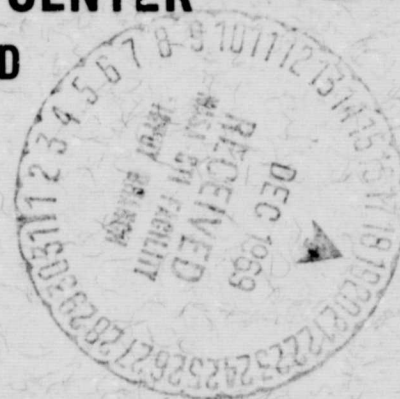
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PREPARATION OF MIRROR COATINGS FOR THE VACUUM
ULTRAVIOLET IN A TWO-METER EVAPORATOR*

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November 1969

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ABSTRACT

The design and features of a two-meter evaporator suitable for coating large mirrors uniformly with Al + MgF_2 and Al + LiF films of high reflectance in the vacuum ultraviolet are described. The techniques used for monitoring film thicknesses during the film deposition and for producing films of uniform thicknesses over large areas are discussed. It is shown that the Al films for MgF_2 - and LiF-protected mirrors of highest reflectance in the vacuum ultraviolet down to 1000 \AA should be 700 to 800 \AA thick. Data on the vacuum ultraviolet reflectance of Al coated with MgF_2 films of various thicknesses are presented. It was found that mirror coatings prepared in a large evaporator have a higher reflectance in the vacuum ultraviolet than those deposited under the same vacuum and deposition conditions in a small vacuum unit. At $\lambda = 1216 \text{ \AA}$, the reflectance of Al overcoated with 250 \AA of MgF_2 was measured to be about 85%.

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PREPARATION OF MIRROR COATINGS FOR THE VACUUM ULTRAVIOLET IN A TWO-METER EVAPORATOR

INTRODUCTION

Since the development of MgF_2 - and LiF -overcoated aluminum mirrors with high reflectance in the vacuum ultraviolet,¹⁻⁴ coatings of this type have been used in many high-resolution rocket and satellite spectrographs for studying the emission lines of the sun and of stars. Most of these studies were performed with equipment using rather small optical elements. Progress in space technology now makes it possible to place large astronomical mirrors in orbit and the launching of orbiting astronomical observatories (OAO) with mirrors of about 1 meter in diameter is planned in the near future. Today such mirrors can be made with an accuracy of about $1/50$ of a wavelength. In order to maintain this figure accuracy and to make such mirrors most efficient, a technique suitable for applying coatings of uniform and precisely controlled thickness and of high reflectance has to be used. This paper describes the design and features of a 2-meter evaporator suitable for coating large mirrors with films of high reflectance in the vacuum ultraviolet. The techniques used for monitoring film thicknesses during the film deposition and for producing films of uniform thickness over large areas will be discussed. Data on the reflectance of mirror coatings prepared under various conditions in the 2-meter evaporator will be presented. It will be shown that mirror coatings prepared in a large evaporator have a higher reflectance than those deposited under the same vacuum and deposition conditions in a smaller vacuum unit.

TWO-METER EVAPORATOR AND ITS FEATURES

Figure 1 shows a schematical drawing of the evaporator and its features. Two such vacuum units are presently in use, one at the Night Vision Laboratory of the U.S. Army Electronics Command in Fort Belvoir, Virginia, and the other at the Goddard Space Flight Center, NASA, Greenbelt, Maryland. The coating chamber is 2 meters in diameter and about 2 meters high. It is constructed of 304 stainless steel and consists of a vertical cylinder with a curved bottom and a flanged removable lid. A flanged opening at the center of the bottom is fitted with a 75-cm diameter baseplate for supporting the evaporation sources. This plate is mounted on a cart containing the power supply for the evaporation sources and a hydraulic mechanism for raising and lowering the plate. When the plate is lowered, the cart can be pulled from under the tank so that the operator may load, reload or replace the evaporation sources. The evaporation sources, located within a few inches of the baseplate, are connected to copper leads large enough to carry several thousand amperes without excessive heating.

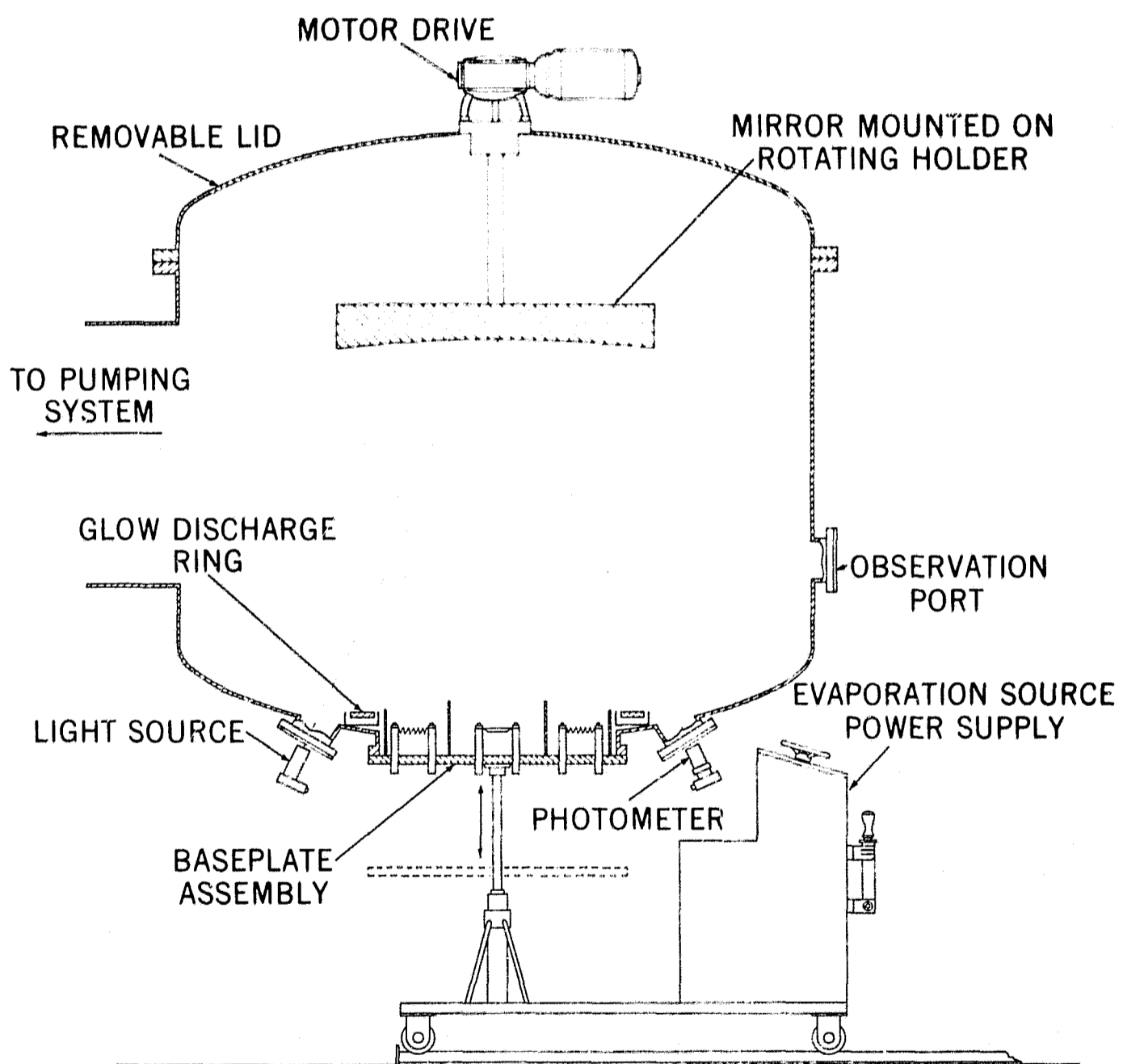


Figure 1. Sketch of the 2-meter evaporator and its features

This permits the use of heavy heating elements, and makes it possible to deposit aluminum films from helical tungsten coils at very high rates using a low-voltage 15 kw power supply. For evaporating platinum and iridium films of high reflectance in the extreme ultraviolet in the 2-meter evaporator a 10 kw electron gun has been used. A detailed description of the technique suitable for evaporating these two materials by electron bombardment has been previously published.⁵

The top of the chamber with the removable lid projects through a second floor where the operator can insert and remove mirror forms and maneuver the cover into position with an electrically driven hoist. A mechanical feedthrough shaft with a motor drive support, located in the center of the lid, allows mirror forms to be rotated during the film deposition in order to achieve coatings of uniform thicknesses over large areas. Three viewing ports at eye level, shielded from the evaporants with solenoid operated venetian blind-type shutters, allow the observation of the interior of the chamber during the evaporation process. Two quartz glass windows, adjacent to the baseplate opening, allow the monitoring of film thicknesses during their deposition by reflectance measurements with monochromatic light. A visible or ultraviolet light source can be used. The light source and photomultiplier housing of the reflectance monitoring system are indicated in Figure 1. Three additional openings in the bottom of the chamber accommodate feedthroughs for vacuum gauges, electrical and mechanical controls, and for gas inlet and needle valves. A circular aluminum glow discharge cathode consisting of a 10 cm wide aluminum ring is placed, insulated from the grounded tank, at the bottom of the chamber. It is connected to a dc high voltage power supply capable of furnishing 15 kv and 500 ma. A glow discharge produced with 6 kv and 500 ma was found to be sufficient to clean the substrate before the coating is applied. To produce films with excellent adherence to the substrates, it was found advantageous to evacuate the tank first to coating pressure before starting the glow discharge cleaning. This procedure reduces the time between the discharge cleaning and the coating cycle which should be kept to a minimum. The glow discharge is performed with O₂ admitted to the chamber through a needle valve.

Shutters are placed over the evaporation sources to avoid contamination of the mirror substrates while the filaments and boats with the evaporants are being outgassed and brought to evaporation temperature. The chamber is lined with interchangeable stainless steel shields to make the removal of accumulated coatings more convenient.

The tank is evacuated with a 50-cm oil diffusion pump backed by a Roots-type mechanical booster and a mechanical forepump. A chevron-type cold baffle, which is cooled with liquid nitrogen, and poppet-type valve are stationed between the chamber and the diffusion pump. The pumping system is capable of producing an ultimate pressure of 1×10^{-7} torr in the chamber.

A special substrate holder was used to study the effect of MgF_2 and LiF thickness on the vacuum ultraviolet reflectance of fluoride-overcoated aluminum mirrors. A sketch of the arrangement is shown in Figure 2. With this arrangement the holder is first placed in a horizontal position in which all glass substrates are coated with opaque aluminum of uniform thickness. The frame is then tilted to place the aluminum coated glass plates at various distances from the MgF_2 or LiF evaporation source. This allows the simultaneous evaporation of fluoride films of different thicknesses onto the opaque aluminum coatings. The thickness of each fluoride film is calculated using a previously determined thickness distribution function and the thickness measured at the center by Tolansky's multiple beam interferometer technique.⁶ With a tilt angle of 45° a fluoride thickness range extending from 100 Å to 350 Å was obtained for a 250 Å thick fluoride film at the center. The same tilted arrangement can be used to study the effect of film thickness on the reflectance of other film materials such as platinum and iridium which are known to require a certain thickness for maximum reflectance in the vacuum ultraviolet.^{5,7}

TECHNIQUES USED FOR MONITORING FILM THICKNESSES AND FOR PRODUCING FILMS OF UNIFORM THICKNESS

To obtain MgF_2 - and LiF -protected aluminum mirrors with the highest reflectance in the vacuum ultraviolet special consideration must be given to the proper thickness of the component films. The aluminum film should be kept thin but, at the same time, thick enough to be opaquely reflecting at wavelengths longer than 1000 Å. An excessive thickness introduces increased surface roughness and undesired scattering. Using the optical constants of aluminum published by Hunter,⁸ the reflectance of aluminum as a function of film thickness was calculated for $\lambda = 1026$ Å and $\lambda = 1216$ Å. The calculations were performed with a digital computer using the general film-calculation program developed by Berning and Berning.⁹ The results are shown in Figure 3. At a film thickness of about 800 Å the calculated reflectance of an aluminum film is less than 0.05% lower than that of a completely opaque one for both $\lambda = 1026$ Å and $\lambda = 1216$ Å. A reduction of the film thickness to 600 Å causes a decrease in the calculated reflectance of approximately 0.5%. Similar results were obtained for the calculated reflectance of MgF_2 - and LiF -overcoated aluminum as a function of aluminum thickness. Therefore, the aluminum thickness for MgF_2 - and LiF -protected mirrors does not need to exceed 700 to 800 Å to obtain the highest possible efficiency for all wavelengths longer than 1000 Å. The use of thicker aluminum films will, in practice, even result in mirrors with lower specular reflectance because the surface roughness increases with increasing film thickness.

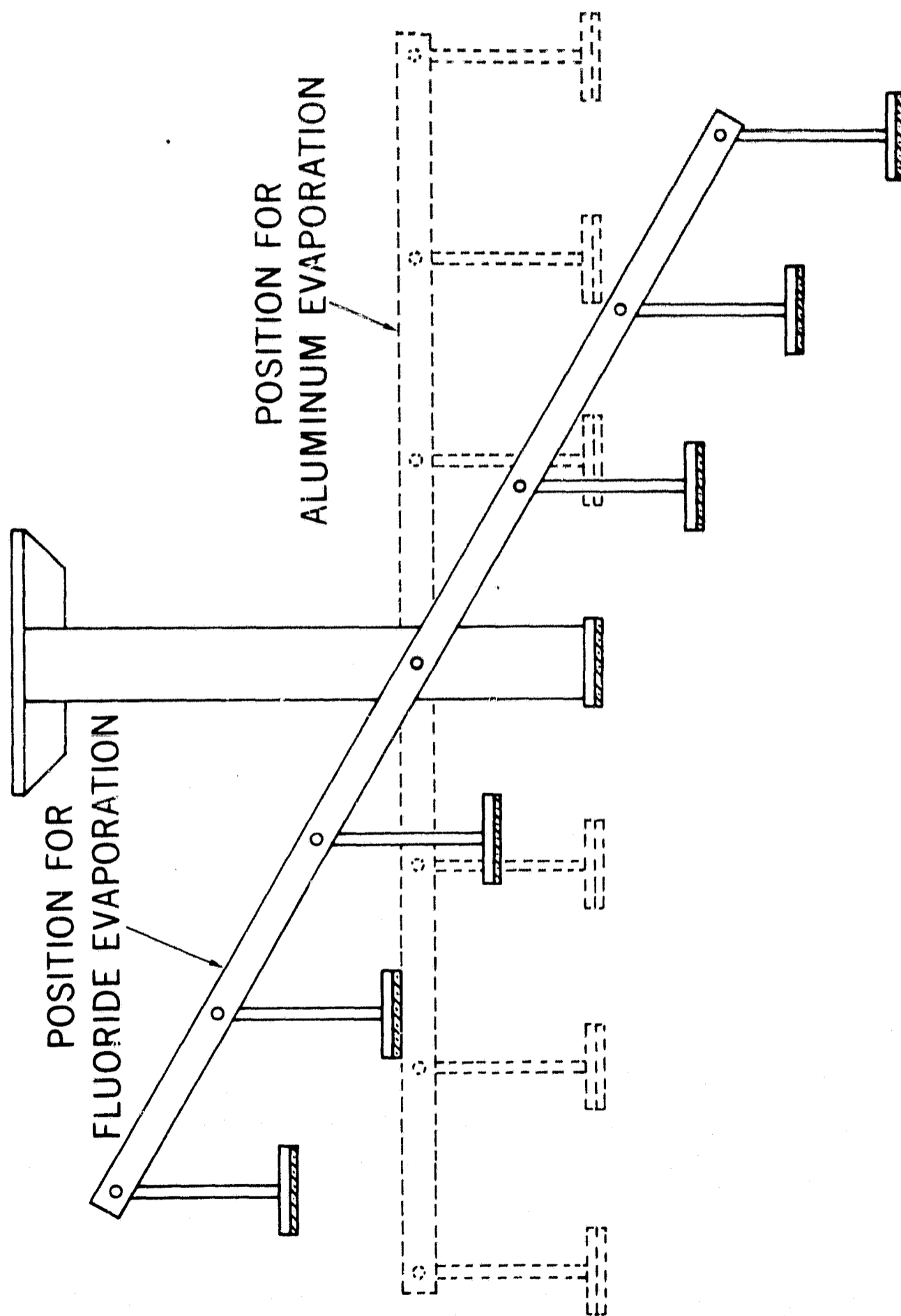


Figure 2. Sketch of the substrate holder used to study the effect of fluoride thickness on the reflectance of MgF_2 and LiF -protected Al mirrors.

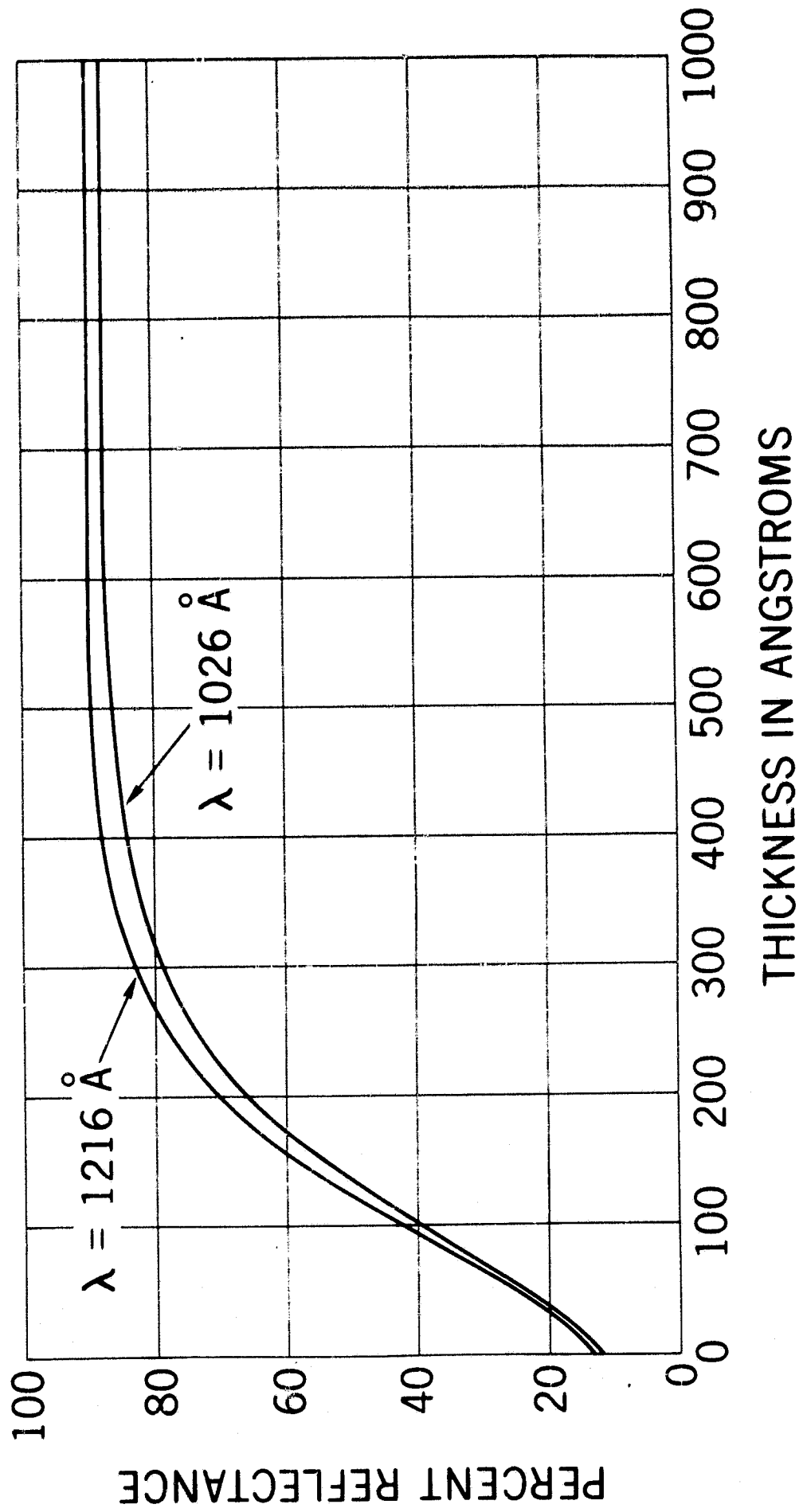


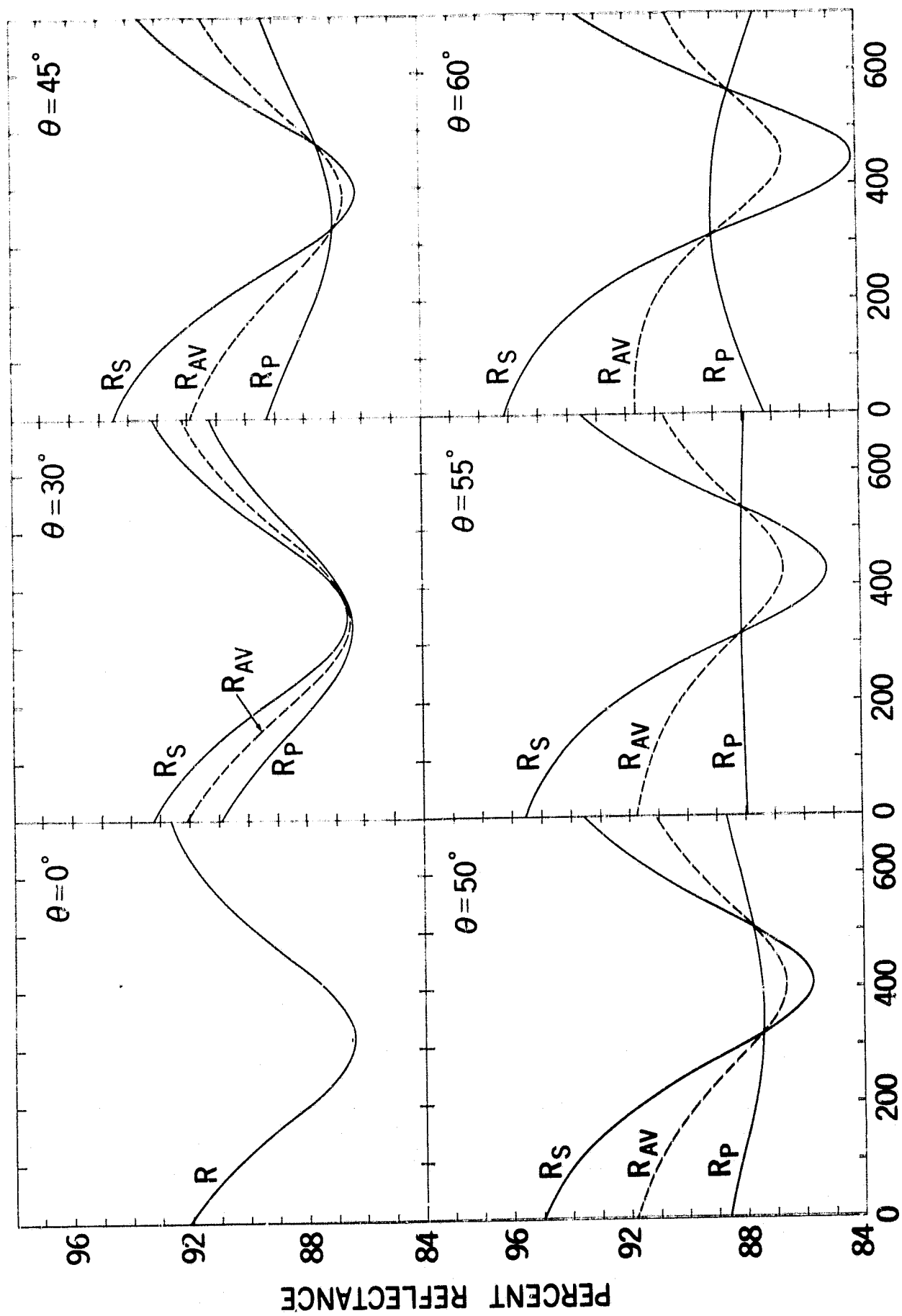
Figure 3. Calculated reflectance of Al as a function of thickness for $\lambda = 1026 \text{ \AA}$ and $\lambda = 1216 \text{ \AA}$.

Since the acceptable thickness range for the aluminum film is broad, rather simple techniques may be used to control its thickness during the film deposition. Among those used most frequently are a visual method where the observer looks at the bright aluminum evaporation sources through a clear glass plate until the coating becomes just opaque, and a timed interval technique in which the aluminum thickness is determined by timing the duration of the evaporation. With these simple methods, aluminum films of the desired thickness of 800 Å can be routinely made with a reproducibility of about ± 100 Å. A more accurate monitoring of the film thickness can be achieved by the use of a quartz crystal oscillator.¹⁰

As previously reported, the optimum thicknesses of the MgF_2 and LiF protective coatings on aluminum for maximum reflectance at $\lambda = 1216$ Å and 1026 Å are 250 Å² and 140 Å,⁴ respectively. In either case, accurate thickness control is essential. The thickness of LiF protective films, for example, has to be controlled within ± 10 Å. The optical monitoring system shown in Figure 1 was designed to monitor the near normal incidence reflectance during the film deposition process. Major components of the system are a low pressure mercury lamp followed by a collimator and a photometer using an RCA 1P28 photomultiplier as detector and a narrow band interference-type transmission filter for producing monochromatic light. In principle, the reflectance may be monitored at any convenient wavelength in the Hg spectrum. The 2537 Å line of Hg was selected, because Canfield et al.² showed that reflectance monitoring at such a short wavelength gives considerably greater sensitivity than monitoring at longer wavelengths. Monitoring at shorter wavelength with the extremely intense 2537 Å line of Hg also reduces stray light interference in the photometer thereby eliminating the need for a chopped-beam photometric system.

Two techniques have been used to monitor the thickness of the MgF_2 - and LiF -overcoatings. The first, as previously described,² involves measurement of the reflectance of an uncoated glass plate which is shielded during the aluminum deposition but exposed during the fluoride evaporation. If the glass plate is located in the same plane as the mirror being coated, the reflectance decrease corresponding to the appropriate overcoating thickness is determined from a suitable monitoring curve. Alternately, the sensitivity of this technique may be greatly increased by placing the monitoring plate closer to the fluoride evaporation source.

The second thickness monitoring technique measures the reflectance change of the freshly deposited aluminum film as the MgF_2 or LiF is deposited. Major advantages of this method are elimination of a mechanism for shielding the glass plate during the aluminum deposition and the possibility of monitoring directly from the mirror being coated. As in the first method, the reflectance is measured at $\lambda = 2537$ Å and the glass plate may be placed in either of the two locations



THICKNESS IN ANGSTROM UNITS

Figure 4. Calculated reflectance of Al + MgF₂ as a function of MgF₂ thickness at $\lambda = 2537 \text{ \AA}$ for various angles of incidence.

described previously. Since the change in reflectance is small, however, it is essential that the major portion of the output signal be suppressed and the upper 10% to 20% expanded to full scale preferably on a chart recorder. Calculated reflectance curves for monitoring the MgF_2 thickness on freshly deposited aluminum at $\lambda = 2537 \text{ \AA}$ at normal and at various angles of incidence are shown in Figure 4. The optical constants of aluminum published by Hass and Waylonis¹¹ and of MgF_2 reported by Hall¹² were used for the calculations. The angle of incidence in the 2-meter evaporator when monitoring directly from the mirror being coated is close to 30° . The calculated reflectance change for 250 \AA of MgF_2 on aluminum caused by unpolarized light is approximately 4.5%, which corresponds to a change from 100 to 95 scale divisions on our expanded scale. The actual measured change caused by 250 \AA of MgF_2 was found to be slightly smaller, 100 to 95.6. This is mainly caused by the effect that the refractive index of freshly deposited MgF_2 is smaller than that of MgF_2 measured after exposure to air. Figure 4 also illustrates the polarization dependence for the reflectance of $\text{Al} + \text{MgF}_2$ as a function of MgF_2 thickness at $\lambda = 2537 \text{ \AA}$ for various angles of incidence. For direct monitoring of 250 \AA of MgF_2 on aluminum at close to normal incidence, the reflectance changes for polarized and unpolarized light are about 5%. At larger angles of incidence, the reflectance change caused by the same thickness of MgF_2 with unpolarized light decreases from 4.5% at 30° to 1.5% at 60° while that for the s-polarized component decreases from 5% to 4.5% and the use of p-polarized light becomes essentially ineffectual. When monitoring a 250 \AA MgF_2 film, therefore, the use of s-polarized light yields a slight advantage for incidence angles up to about 30° and is considerably more sensitive for larger angles. Larger reflectance variations and greater sensitivity may be obtained by monitoring to the reflectance minimum on a separate monitoring sample which must be located below the mirror to allow for an increased thickness of the MgF_2 film. With this technique, a reflectance change of approximately 5% is observed with unpolarized light for all angles of incidence up to 60° , while for the s-polarized component the change increases from 6.5% at 30° to 12% at 60° . Since the index of refraction for MgF_2 and LiF are nearly the same at $\lambda = 2537 \text{ \AA}$ the monitoring curves shown in Figure 4 may also be used for producing $\text{Al} + \text{LiF}$ coatings by making slight adjustments via a trial and error technique.

Methods for producing MgF_2 - and LiF -protected aluminum mirrors with diameters in excess of 50 cm must necessarily start with a consideration of the thickness uniformity of the aluminum coating and its influence on the mirror contour. Using a circular array of filaments of about 55 cm in diameter to deposit an aluminum film 1000 \AA thick at the center of a 1-meter diameter mirror located 1 meter above the vapor sources results in a thickness distribution which is nearly symmetrical about the center of the mirror and decreases to approximately 600 \AA at the edge. This thickness is still sufficient to insure

high reflectance for all wavelengths longer than 1000 \AA , but significantly alters the contour of a mirror figured to $1/50$ of a wavelength at $\lambda = 5000 \text{ \AA}$. For accurately figured mirrors, therefore, a technique for correcting the aluminum thickness distribution must be employed. The method selected for correcting the aluminum thickness consists of placing a circular baffle above the filaments at a height which partially masks the center of the mirror as illustrated in Figure 5. The correct diameter and height were estimated by geometrical construction and refined by experimental trial and error. Typical results for the thickness distributions, obtained with and without the baffle plate, are shown in Figure 6. Thicknesses for the thick films, as determined interferometrically using the Tolansky method, have an average value of 720 \AA with a root mean square error of $\pm 60 \text{ \AA}$. The distribution for the thinner films, as determined from transmittance measurements corrected for oxidation effects, yielded an average of 175 \AA with a variation of approximately $\pm 15 \text{ \AA}$. Data for the thinner films was included since aluminum films in the 100 \AA to 200 \AA thickness range may be used for producing large diameter beam splitters or ultraviolet filters.

The arrangement used for depositing Al and fluoride films of uniform thickness on large mirrors and for monitoring the thickness of the fluoride films during deposition is illustrated in Figure 7. MgF_2 or LiF is evaporated from a centrally located shallow tungsten boat and the above described array of filaments is employed for the deposition of Al. Behrndt¹⁰ has demonstrated that the vapor distribution from a shallow boat can be corrected to produce a uniform film thickness on large mirrors by using a specially designed rotating baffle. The arrangement shown in Figure 7 was designed¹³ to deposit fluoride films of uniform thickness on a plane or a concave mirror with large radius of curvature by rotating the mirror instead of the baffle. To determine the thickness uniformity attainable with this arrangement, a fixture simulating a 1-meter diameter mirror with a 4-meter radius of curvature was constructed to hold a number of 5-cm square samples at selected radial distances. MgF_2 was then deposited to a thickness of approximately 1500 \AA on the samples under the same conditions that would be used to coat a mirror with Al + MgF_2 . The thickness on each sample was subsequently measured by the multiple beam interferometer technique and the resulting thickness distribution is shown in Figure 8 where the thickness has been scaled to a MgF_2 film 250 \AA thick. A linear least squares analysis of the data yielded a root mean square deviation of about $\pm 10 \text{ \AA}$ which is within the error of the thickness measurements. The same procedure and baffle was then used to determine the thickness distribution of the Al films deposited from the array of filaments. Results for this test yielded an average thickness of 650 \AA with a root mean square deviation of $\pm 10 \text{ \AA}$ and are also shown in Figure 8. It may be considered extremely fortunate that the baffle used for correcting the fluoride thickness distribution also corrects that of the Al films.

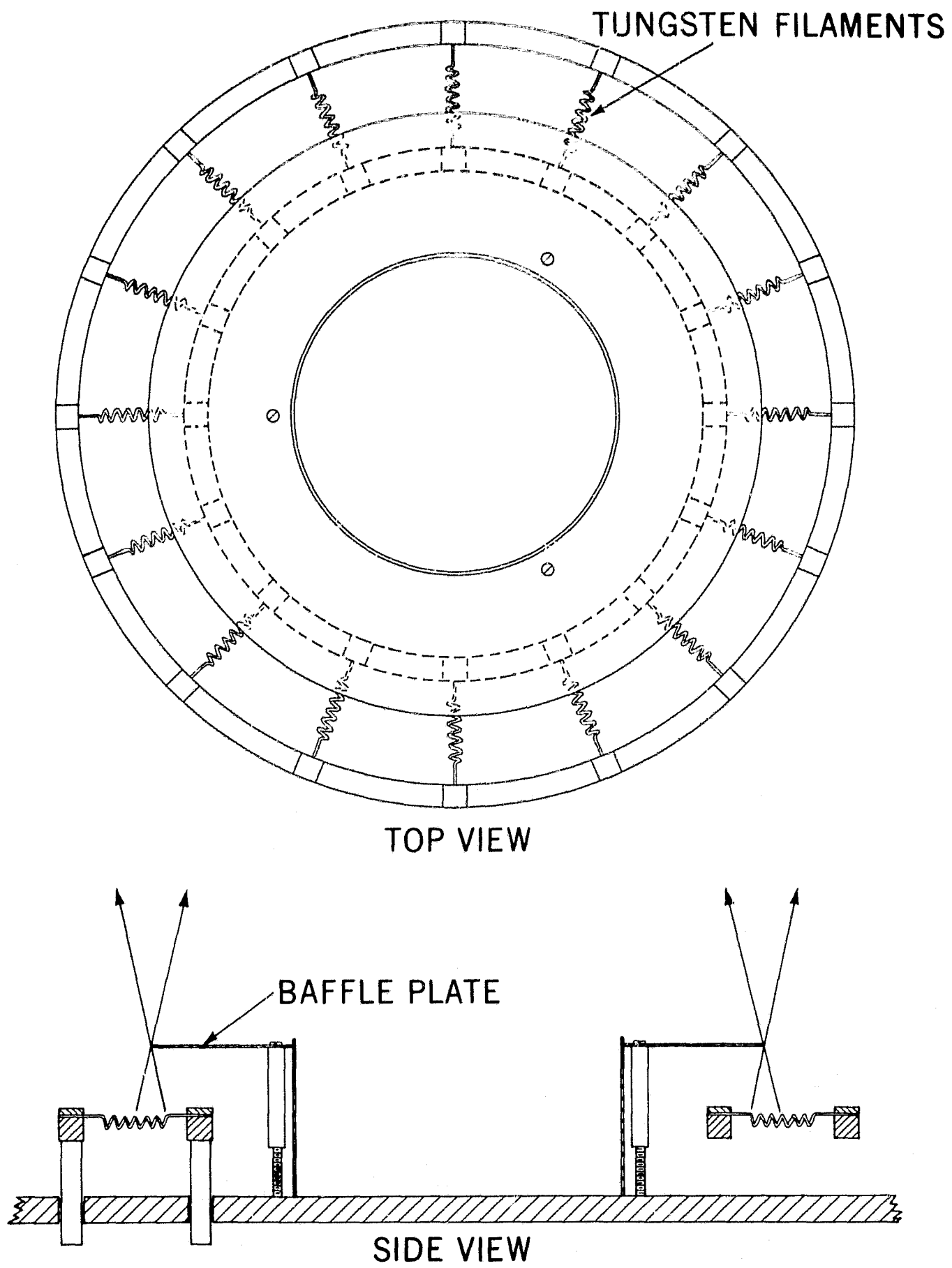


Figure 5. Arrangement used for producing Al films of uniform thickness over large areas without substrate rotation.

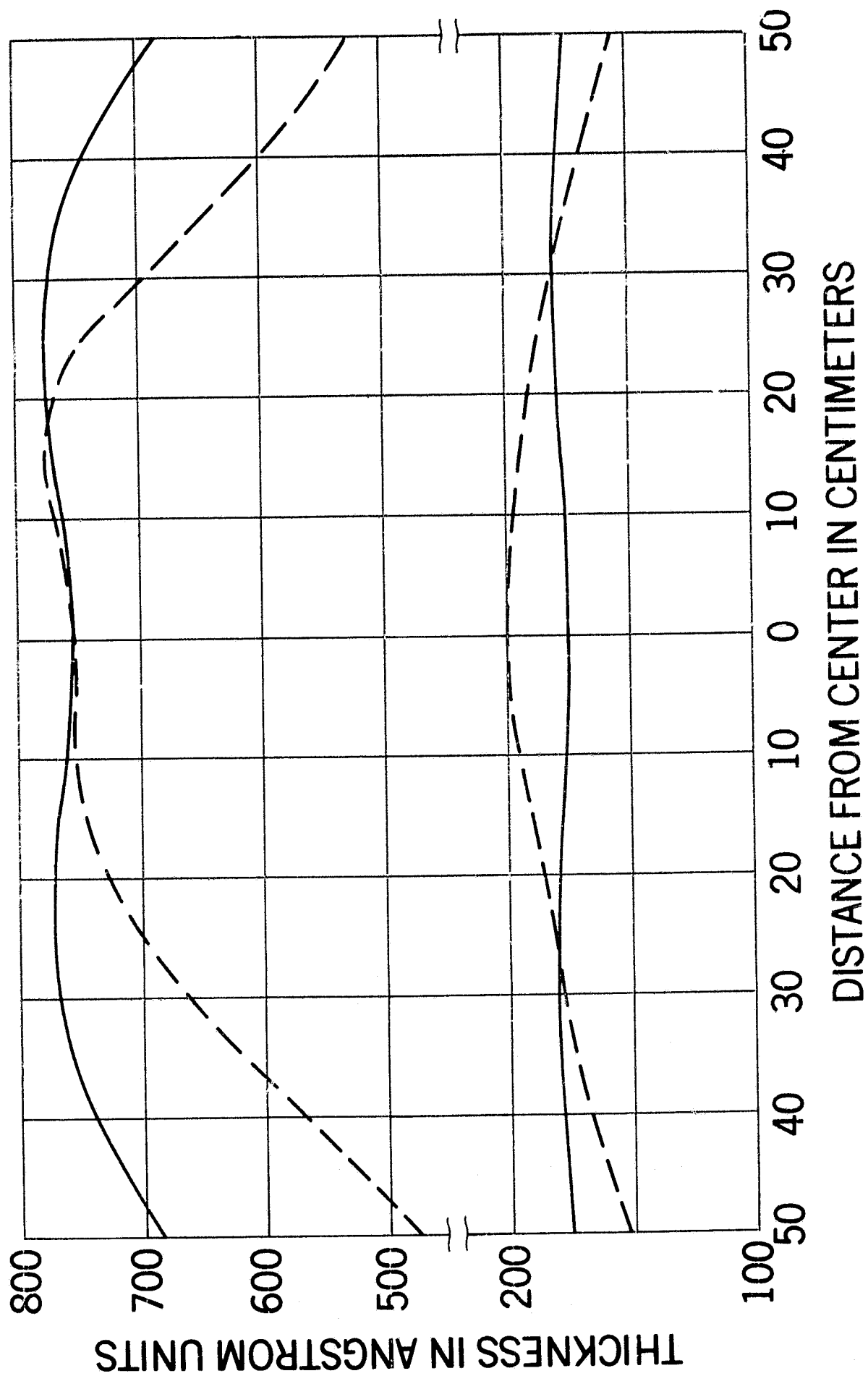


Figure 6. Al thickness distribution obtained over a 1-meter in diameter with (solid line) and without (dashed line) the use of a baffle plate over the filaments.

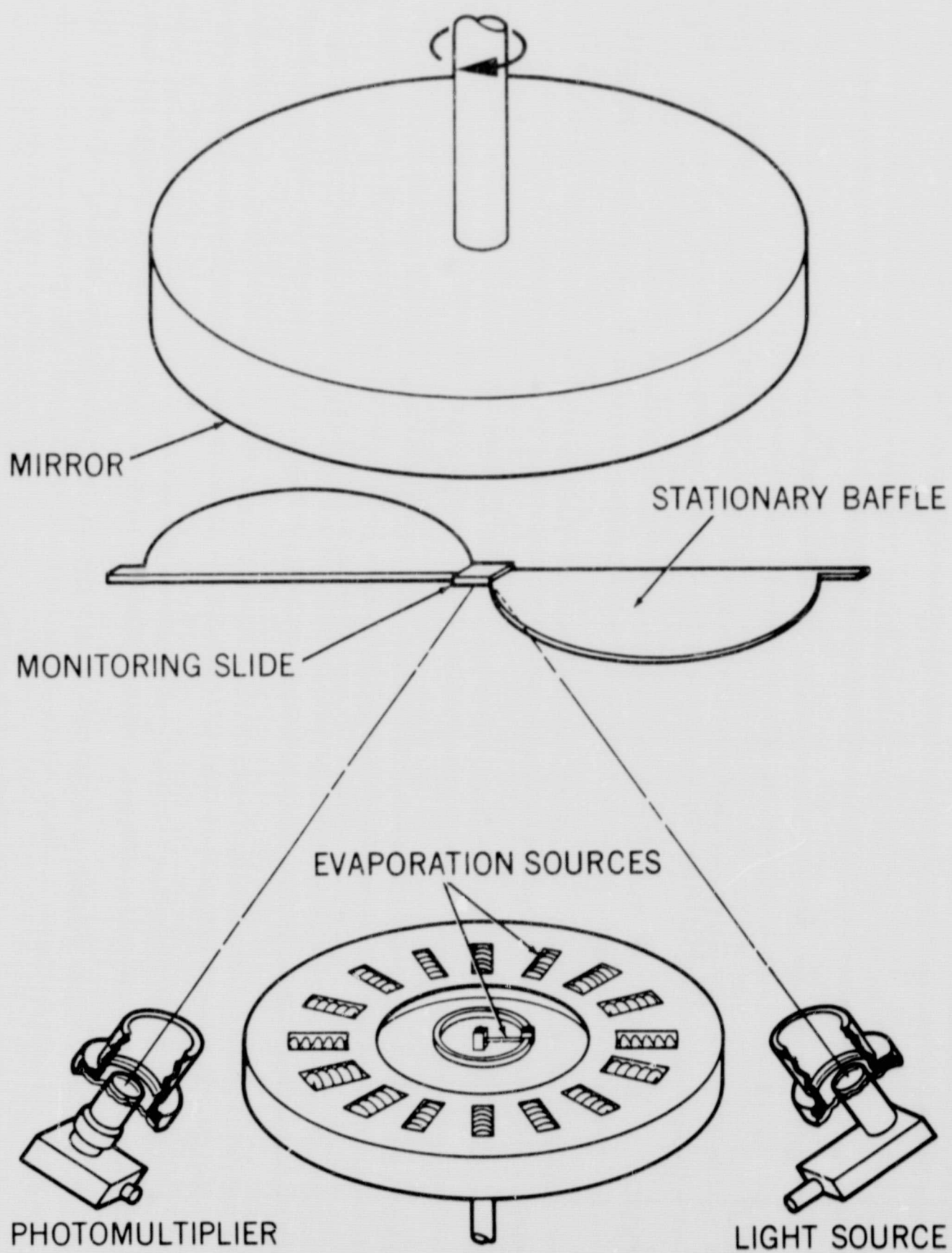


Figure 7. Sketch of the arrangement used for producing Al and fluoride films of uniform thickness over large areas and for monitoring the thickness of the fluoride films during their deposition.

APPENDIX PULSE DESENSITIZATION MEASUREMENTS

A. GENERAL

The pulse desensitization measurements were conducted as a result of the wide divergences between the predicted and measured values of the pulsed radars in the power density tests.

The following information was extracted from "Spectrum Analysis - Application Note Sixty-Three," May 1965, page 23 of C. Measuring Absolute RF Levels, by the Hewlett-Packard Company:

One further consideration must be made about the analyzer at this point and that is pulse desensitization. When measuring pulsed signals and comparing their spectrum amplitudes with those for CW signals, the shape and bandwidth of the IF amplifier in the analyzer must be shown. Because the analyzer must be selective for resolving spectra, its IF bandwidth does not admit all of the frequency components contained in a pulse at one time. Therefore, the peak amplitude of the main lobe of a pulse's spectral display is typically 20 dB lower than the response to a CW signal of equal peak value to that of the pulse. This is termed pulse desensitization and is given in terms of dB loss by the equation $\alpha = 20 \log K t \Delta f$ where

α = attenuation of pulse spectrum main lobe relative to a CW signal of equal strength.

K = an IF bandshape constant for the particular 851A being used.

t = measured pulse width in sec.

Δf = IF bandwidth selected on the analyzer.

B. POLARAD CFI RECEIVER PULSE DESENSITIZATION/BANDWIDTH MEASUREMENT

1. Purpose. This test was conducted to measure the difference in the signal levels caused by the receiver not capturing the entire bandwidth occupied by the pulsed radar signal.

2. Test Facility and Equipment. These measurements were performed in the EMC Laboratory, using the following equipment:

- | | | | |
|----|------------------|---|------------------------|
| a. | Receiver | - | Polarad CFI |
| | | - | Tuning Heads CFI (M&S) |
| b. | Signal Generator | - | Rohde and Schwarz SHF |
| | | - | HP-8616 |

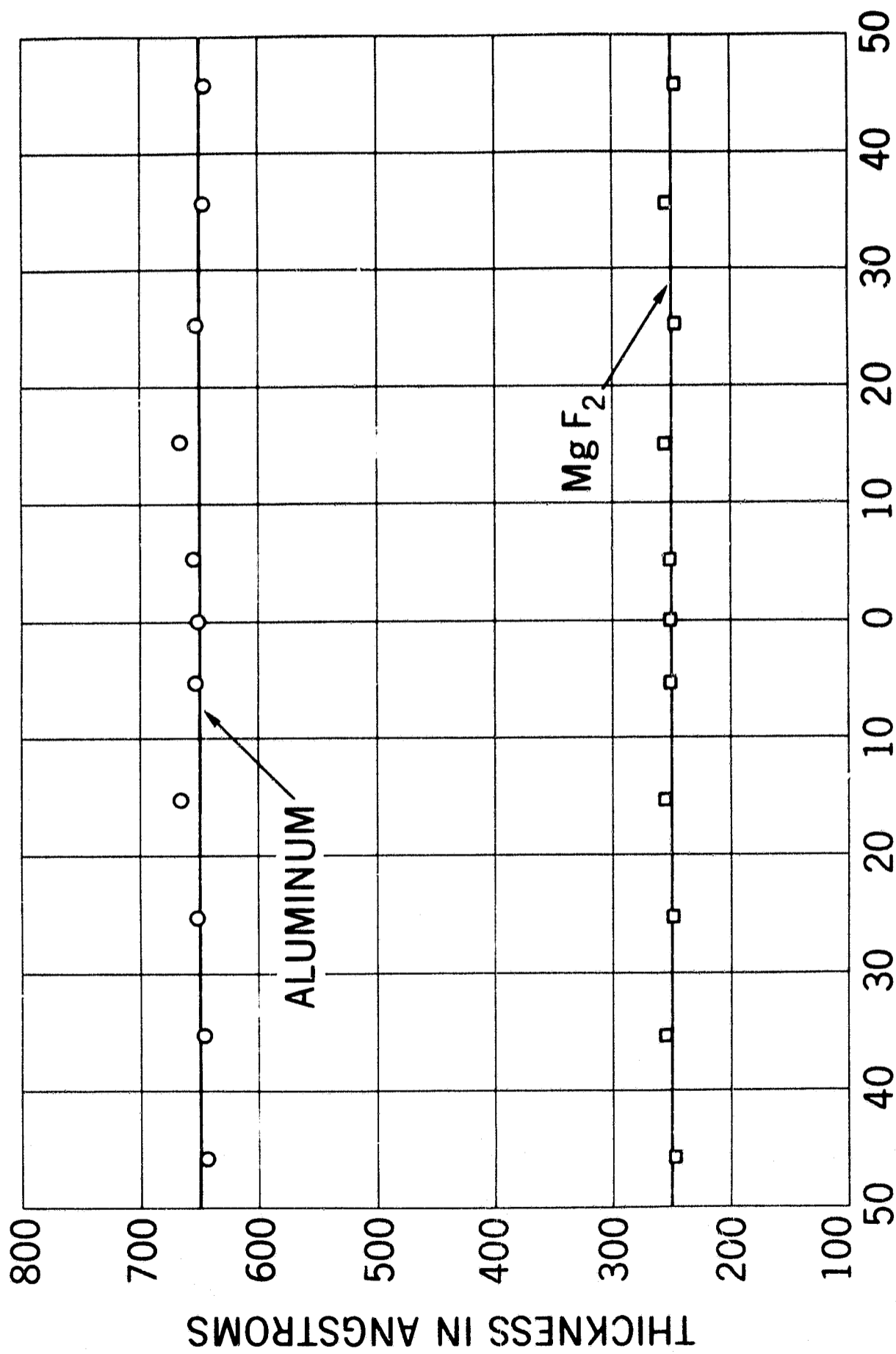


Figure 8. Al and MgF₂ thickness distribution obtained over a 1-meter in diameter area using a stationary baffle and rotating mirror.

Monitoring of the MgF_2 and LiF thickness is accomplished by measuring the reflectance of a monitoring slide mounted at the center of the stationary baffle with monochromatic light of $\lambda = 2537 \text{ \AA}$. This slide will be coated with a thicker film of MgF_2 than the mirror which makes this technique more sensitive.

REFLECTANCE OF MgF_2 - AND LiF -OVERCOATED Al MIRRORS PREPARED UNDER VARIOUS CONDITIONS

Previous experimental studies of MgF_2 -protected Al mirrors have indicated that maximum reflectance at $\lambda = 1216 \text{ \AA}$ is obtained with a MgF_2 thickness of 250 \AA .² These studies were performed using individually prepared samples of Al overcoated with various thicknesses of MgF_2 . With such samples, slight variations in the deposition conditions for the Al films, however, may introduce an uncertainty in the experimentally determined reflectance of Al + MgF_2 as a function of MgF_2 thickness. Using the special substrate holder shown in Figure 2, which allows the simultaneous evaporation of Al films of uniform thickness and MgF_2 overcoatings of various thicknesses, a more accurate determination of the effect of MgF_2 thickness on the reflectance of Al + MgF_2 mirrors could be made. With the substrate holder in the horizontal position a uniform Al film is deposited using the circular array of filaments and the baffle arrangement shown in Figure 5. The holder is then tilted through a predetermined angle and the MgF_2 deposited.

Reflectance studies at $\lambda = 1216 \text{ \AA}$ as a function of MgF_2 thickness for several sets of samples prepared in this manner were averaged and are illustrated in Figure 9 compared to the calculated reflectance using the optical constants for Al and MgF_2 reported by Canfield et al.² In agreement with previous results,² the reflectance maximum was observed at a MgF_2 thickness of $250 \text{ \AA} \pm 15 \text{ \AA}$. Peak reflectance at $\lambda = 1216 \text{ \AA}$, however, was found to be about 85%, which is approximately 2% higher than the value previously published.² The measured reflectance also exhibits a sharper decrease in reflectance about the maximum. Although aging was observed for samples coated with less than 200 \AA of MgF_2 , it was not of sufficient magnitude to explain the difference between the measured and calculated reflectance. No significant aging was observed for MgF_2 -protected Al samples with an overcoating thickness in excess of 250 \AA . The experimentally determined higher peak reflectance and the sharper decrease in reflectance about the maximum indicate, therefore, that the optical constants for MgF_2 should be revised. Additional studies on evaporated and single crystalline material to obtain better optical constants for MgF_2 in the wavelength region from 1100 \AA to 2000 \AA are in progress.

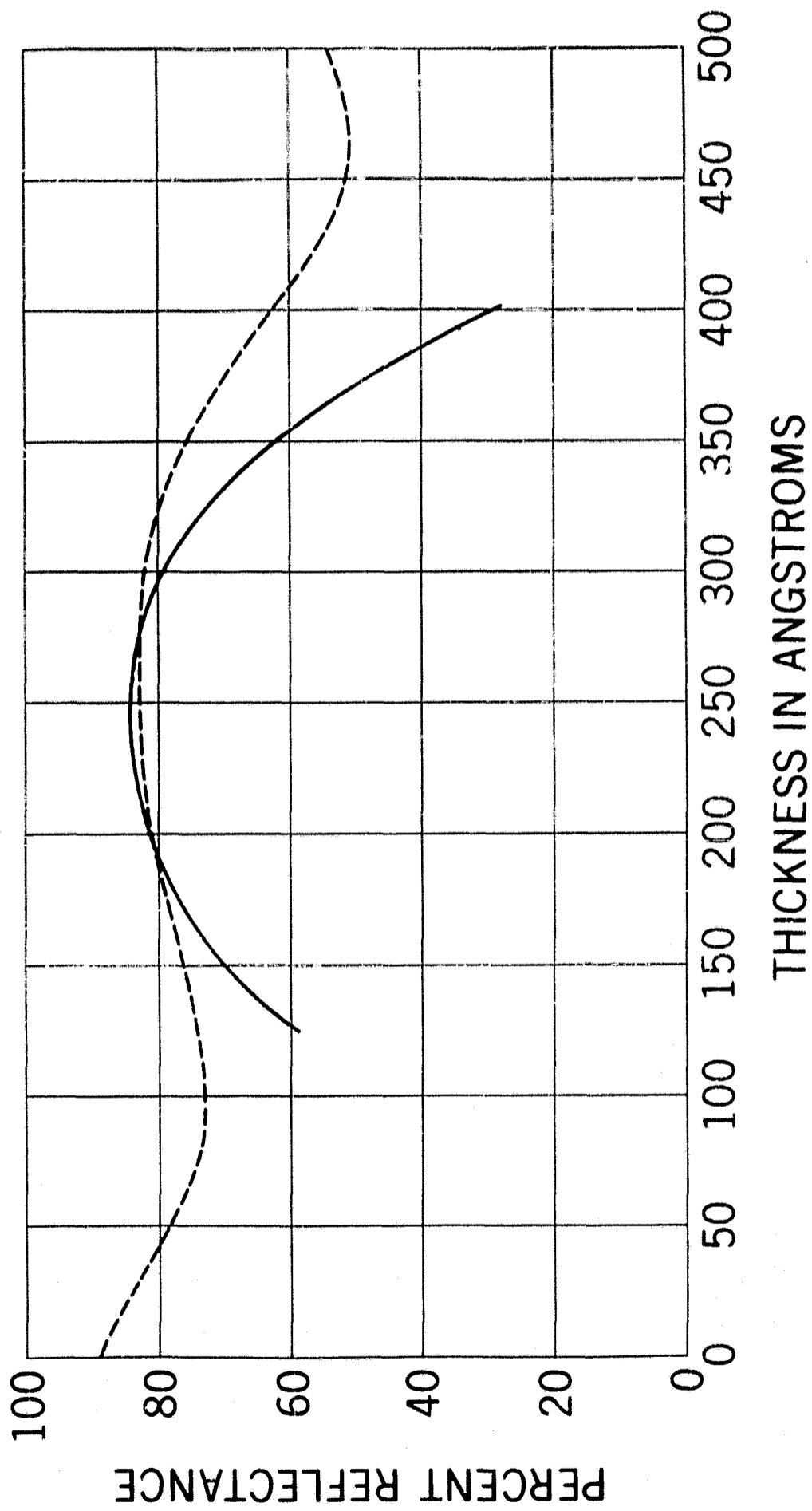


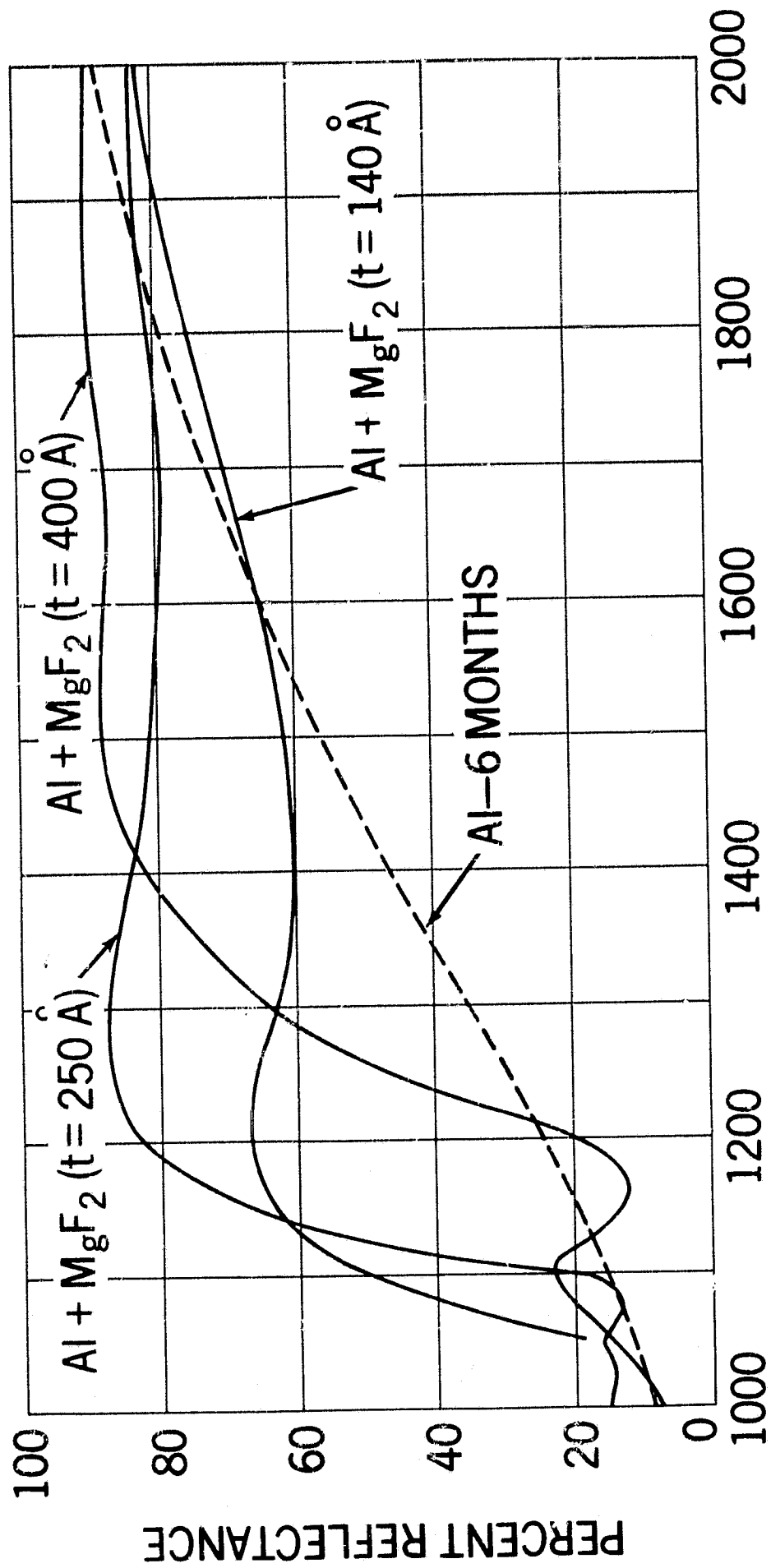
Figure 9. Comparison of the measured (solid line) and calculated (dashed line) reflectance at $\lambda = 1216 \text{ \AA}$ as a function of MgF_2 thickness.

Figure 10 shows the reflectance of evaporated Al overcoated with protective layers of MgF_2 of three different thicknesses in the wavelength region from 1000 Å to 2000 Å. The rates used for the deposition of the two materials were 100 Å/sec for Al and about 30 Å/sec for MgF_2 . When Al is overcoated with 250 Å of MgF_2 , a reflectance of about 85% is obtained at $\lambda = 1216$ Å and reflectance values for all wavelengths longer than 1200 Å remain essentially higher than 80%. A MgF_2 protective coating of 140 Å yields higher reflectance in the 1100 Å region. However, such mirror coatings show aging effects and rather low reflectance at longer wavelengths. Therefore, no significant advantage can be obtained by using thin MgF_2 instead of LiF overcoatings for producing mirrors with high reflectance in the wavelength region below 1150 Å. To increase the reflectance above 1450 Å, thicker overcoatings of MgF_2 should be used. Al overcoated with 400 Å of MgF_2 , for example, exhibits a reflectance of approximately 90% for all wavelengths longer than 1500 Å.

It should be mentioned that MgF_2 -protected Al mirrors produced in smaller vacuum units, such as a 45-cm evaporator, exhibit a much lower vacuum ultraviolet reflectance, when prepared with the rather low Al deposition rates mentioned above. The conditions for preparing Al films of optimum reflectance in small evaporators are much more stringent than those required for producing Al films of maximum reflectance in a large vacuum unit.¹ In small evaporators, Al deposition rates in excess of 500 Å/sec and the use of a high speed shutter placed close to the mirror substrate to be coated are an absolute necessity for producing Al films of maximum reflectance in the vacuum ultraviolet. In the 2-meter evaporator, Al + MgF_2 coatings of more than 80% reflectance at $\lambda = 1216$ Å can be prepared at much lower Al deposition rates and without the use of any shutter.

The reflectance of evaporated Al overcoated with 140 Å of LiF as a function of wavelength from 900 Å to 1900 Å is shown in Figure 11. For wavelengths shorter than 1150 Å such a film combination exhibits a considerably higher reflectance than an Al + MgF_2 mirror coatings. However, the reflectance of Al + LiF coatings decreases greatly at all wavelengths during storage in air of 30% to 50% humidity. This aging effect, which was found to be negligible for Al + MgF_2 coatings,² can be almost completely eliminated by storing Al + LiF coated mirrors in an extremely dry atmosphere. Studies to produce more stable Al + LiF coatings and to determine the aging of LiF coated Al at various humidities are in progress.

Studies of the reflectance distribution over a 1-meter in diameter area were made for both Al + MgF_2 and Al + LiF mirror coatings prepared by the technique discussed above and illustrated in Figure 7. Typical results for MgF_2 protected Al at $\lambda = 1216$ Å and for LiF overcoated Al at $\lambda = 1026$ Å are shown in Figure 12. A linear least squares analysis of the reflectance data for the



WAVELENGTH IN ANGSTROM UNITS

Figure 10. Reflectance of evaporated Al with protective layers of MgF₂ of three different thicknesses in the wavelength region from 1000 Å to 2000 Å.

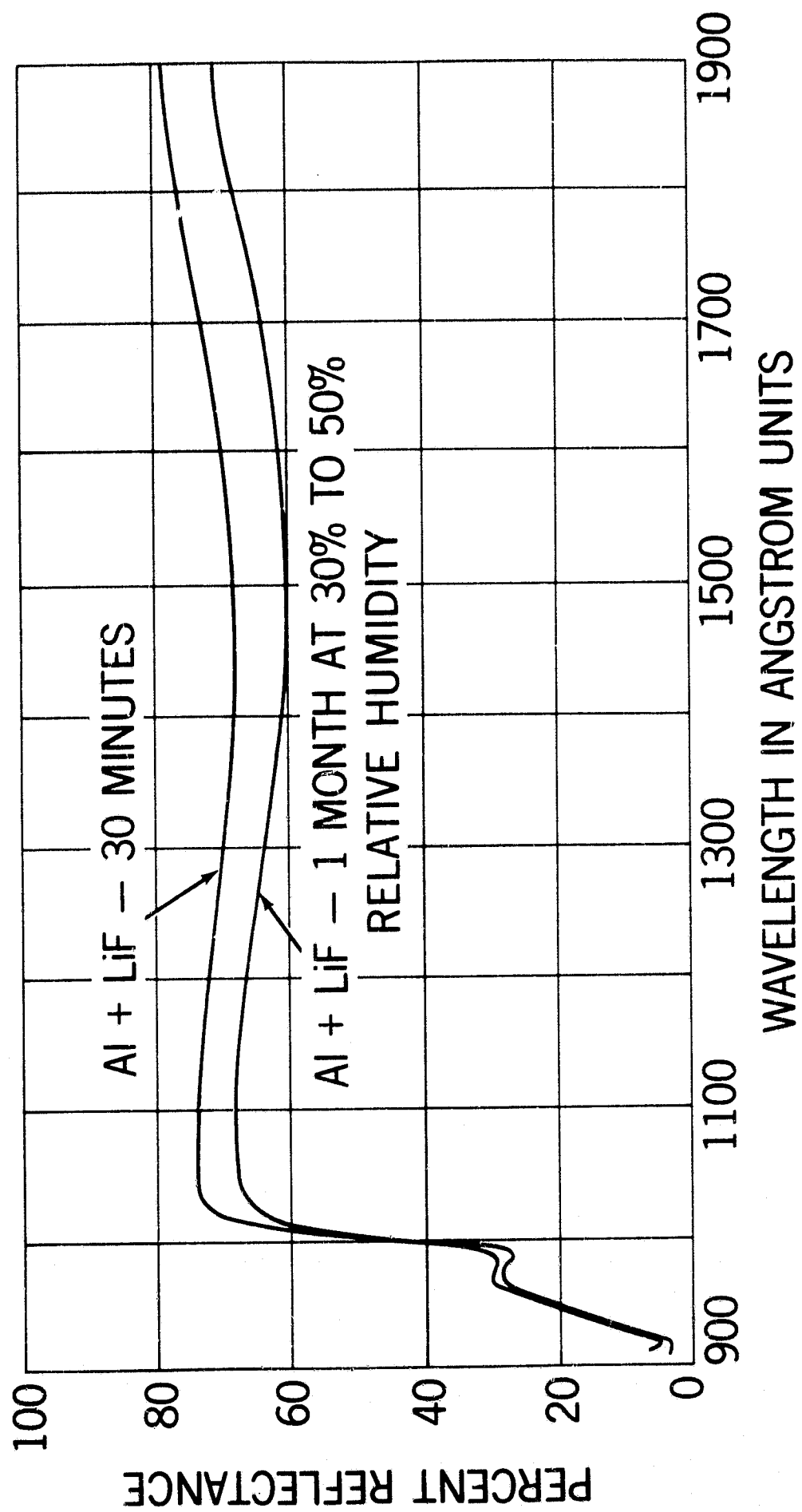


Figure 11. Reflectance of evaporated Al with a 140 Å thick LiF overcoating in the wavelength region from 900 Å to 1900 Å after 30 min and 1 month of exposure to air of 30% to 50% humidity.

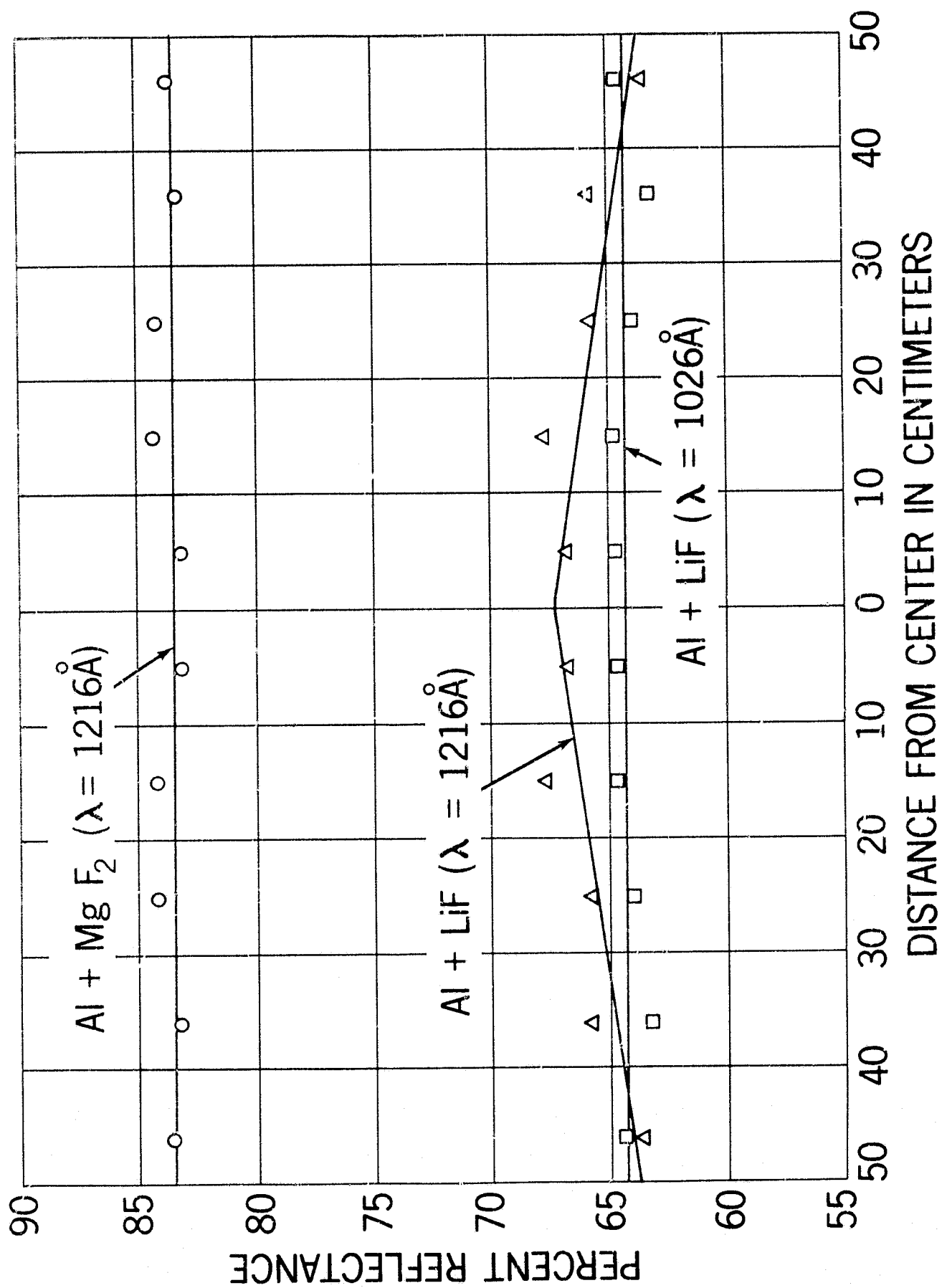


Figure 12. Reflectance of LiF- and MgF₂-overcoated Al at $\lambda = 1216 \text{ \AA}$ and $\lambda = 1026 \text{ \AA}$ over an area 1 meter in diameter.

Al + MgF₂ samples yielded an average reflectance of 83.3% with a root mean square deviation of $\pm 0.3\%$. Based on the reflectance versus MgF₂ thickness measurements shown in Figure 9, the MgF₂ thickness must be uniform to less than $\pm 25 \text{ \AA}$ which is in agreement with the thickness measurements made on MgF₂ films produced under the same conditions. A similar analysis made for Al + LiF samples at $\lambda = 1026 \text{ \AA}$ yields an average reflectance of $65.0\% \pm 0.3\%$. At $\lambda = 1216 \text{ \AA}$, the same samples show a definite radial dependence of the reflectance with a maximum of 67% occurring close to the center and a minimum of 64% at a distance of 45 cm from the center. This unexpected reflectance variation may be explained, in part, by the greater sensitivity to aging which has been observed⁴ for the reflectance of Al + LiF coatings at $\lambda = 1216 \text{ \AA}$. Using the information obtained with a simulated mirror as a guide, several mirrors 1-meter in diameter have been successfully coated with MgF₂ and LiF-protected Al. Although it is not practical to measure the reflectance distribution over the entire mirror area directly, evaluation of samples placed at the center and the extreme edge of the mirrors indicated that the results obtained were consistent with the above results.

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REFERENCES

1. Hass, G. and R. Tousey, J. Opt. Soc. Am. 49, 593 (1959)
2. Canfield, L. R., G. Hass and J. E. Waylonis, Appl. Optics 5, 45 (1966)
3. Angel, D. W., W. R. Hunter, R. Tousey and G. Hass, J. Opt. Soc. Am. 51, 913 (1961)
4. Cox, J. T., G. Hass and J. E. Waylonis, Appl. Optics 7, 1535 (1968)
5. Hass, G., G. F. Jacobus and W. R. Hunter, J. Opt. Soc. Am. 57, 758 (1967)
6. Tolansky, S., Multiple Beam Interferometry of Films and Surfaces, Clarendon Press, Oxford, England, 1948
7. Jacobus, G. F., R. P. Madden and L. R. Canfield, J. Opt. Soc. Am. 53, 1084 (1963)
8. Hunter, W. R., J. Opt. Soc. Am. 54, 208 (1964)

9. Berning, J. A. and P. H. Berning, J. Opt. Soc. Am. 50, 813 (1960)
10. Behrndt, K. H., in Physics of Thin Films Vol 3, eds G. Hass and R. E. Thun, pp. 1 - 60, Academic Press, New York, 1966
11. Hass, G. and J. E. Waylonis, J. Opt. Soc. Am. 51, 719 (1961)
12. Hall, J. F., Jr., J. Opt. Soc. Am. 47, 662 (1957)
13. Herzig, H., NASA Technical Note D-3357 (March 1966)